Restart Strategies and Internet Congestion

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Abstract

We recently presented a methodology for quantitatively reducing the risk and cost of executing electronic transactions in a bursty network environment such as the Internet. In the language of portfolio theory, time to complete a transaction and its variance replace the expected return and risk associated with a security, whereas restart times replace combinations of securities. While such a strategy works well with single users, the question remains as to its usefulness when used by many. By using mean field arguments and agent-based simulations, we determine that a restart strategy remains advantageous even if everybody uses it.

1 Introduction

The impressive growth in the number of Internet users (from 61 million in 1996 to over 150 million today) has led to a radical increase in the volume of data that is transmitted at any given time. Whereas a few years ago email was the preponderant component of Internet traffic, the Web, with its rich and varied content of images and text, makes up for most of the transmitted data today. In addition, financial and other forms of electronic transactions put a premium on mechanisms that ensure timely and reliable transactions in cyberspace. This is an important problem given the bursty nature of Internet congestion [1], which leads to a large variability in the risk and cost of executing transactions.

Earlier, we presented a methodology for quantitatively managing the risk and cost of executing transactions in a distributed network environment [2]. By associating cost with the time it takes to complete the transaction, and risk with the variance in that time, we considered different methods that are analogous to asset diversification, and which yield mixed strategies that allow an efficient trade-off between the average and the variance in the time a transaction will take. Just as in the case of financial portfolios, we found that some of these mixed strategies can execute transactions faster on average and with a smaller variance in their speed.

A potential problem with this portfolio methodology is that if everybody uses it, the latency characteristics of the Internet might shift so as to render the method useless. It this were the case, one would be confronted with a classical social dilemma, in which cooperation would amount to restraining from the use of such strategies and defection on their exploitation [3][4]. Thus it becomes important to determine the effects that many users employing a portfolio strategy have on Internet latencies and their variances. Equally relevant is to determine what the increased latencies are as a function of the fraction of users deciding to employ such strategies.

In order to investigate this issue, we conducted a series of computer simulations of a group of agents deciding asynchronously whether to use the Internet or not. The agents base their decision on knowledge of the congestion statistics over a past window of time. We found that when every agent uses the portfolio strategy there is still a range of parameters such that a) a portfolio exists and b) all agents are better off using it than not. Even when all agents do so, the optimum restart strategy leads to a situation no worse than when no one uses the restart strategy.

2 Restart Strategies

Anyone who has browsed the World Wide Web has probably discovered the following strategy: whenever a web page takes too long to appear, it is useful to press the reload button. Very often, the web page then appears instantly. This motivates the implementation of a similar but automated strategy for the frequent "web crawls" that many Internet search engines depend on. In order to

ensure up-to-date indexes, it is important to perform these crawls quickly. More generally, from an electronic commerce perspective, it is also very valuable to optimize the speed and variance in the speed of transactions, automated or not, especially when the cost of performing those transactions is taken into account. Again, restart strategies may provide measurable benefits for the user.

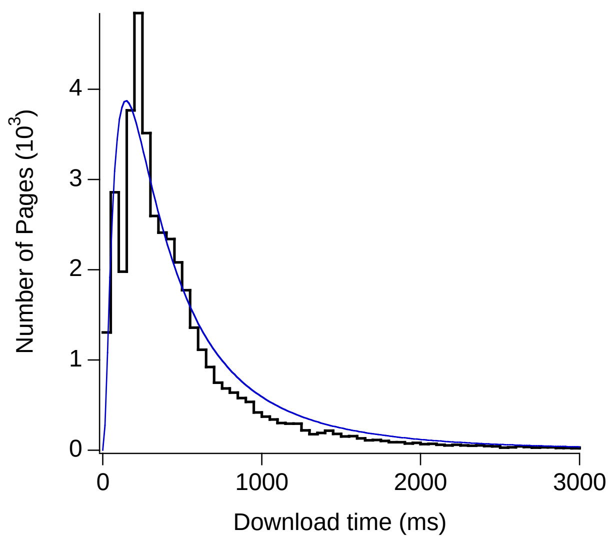

Figure 1: Download time in milliseconds of the index.html file on the main page of over forty thousand web sites, with a fit to a log-normal distribution. The parameters are $\sigma = 0.99$ and $\mu = 5.97$.

The histogram in Figure 1 shows the variance associated with the download time for the text on the main page of over 40,000 web sites. Based on such observations, Lukose and Huberman [2] recently proposed an economics based strategy for quantitatively managing the risk and cost of executing transactions on a network. By associating the cost with the time it takes to complete the transaction and the risk with the variance in that time, they exploited an analogy with the modern theory of financial portfolio management first suggested in a more general context in a previous paper [5]. In modern portfolio theory, the fact that investors are risk-averse means that they may prefer to hold assets from which they expect a lower return if they are compensated for the lower return with a lower level of risk exposure. Furthermore, it is a non-trivial result of portfolio theory that simple diversification can yield portfolios of assets which have higher expected return as well as lower risk. In the case of latencies on the Internet, thinking of different restart strategies is analogous to asset diversification: there is an efficient trade-off between the average time a request will take and the variance or risk in that time.

Consider a situation in which a message has been sent and no acknowledgment has been received for some time. This time can be very long in cases where

the latency distribution has a long tail. One is then faced with the choice to either continue to wait for the acknowledgment, to send out another message or, if the network protocols allow, to cancel the original message before sending out another. For simplicity, we consider the case in which it is possible to cancel the original message before sending out another at the time. $P(t)$, the probability that a page has been successfully downloaded in time less than t, is given by

$$\begin{aligned} P(t) &= p(t) \quad \text{if} \quad t \leq \tau\,, \\ P(t) &= (1 - \int_0^\tau p(t)dt)P(t-\tau) \quad \text{if} \quad t > \tau\,. \end{aligned}$$

where $p(t)$ is the probability distribution for the download time without restart. The latency and risk in loading a page is then given by

$$\begin{aligned} \langle t \rangle &= \int_0^\infty tP(t)dt\,, \\ \sigma &= \sqrt{Var(t)} = \sqrt{\langle (t - \langle t \rangle)^2 \rangle}\,. \end{aligned}$$

If we allow an infinite number of restarts, the recurrence relation above can be solved in terms of the partial moments $M_n(\tau) = \int_0^\tau t^n P(t)dt$:

$$\begin{aligned} \langle t \rangle &= \frac{1}{M_0}(M_1 + \tau(1 - M_0))\,, \\ \langle t^2 \rangle &= \frac{1}{M_0}(M_2 + \tau(1 - M_0)(2\frac{M_1}{M_0} + \tau(\frac{2}{M_0} - 1)))\,. \end{aligned}$$

In the case of a log-normal distribution $p(t) = \frac{1}{\sqrt{2\pi}x\sigma}\exp(-\frac{(\log x - \mu)^2}{2\,\sigma^2})$, $\langle t \rangle$ and $\langle t^2 \rangle$ can be expressed in terms of the error function:

$$M_n(\tau) = \frac{1}{2}\exp(\frac{\sigma^2 n^2}{2} + \mu n)(1 + \mathrm{erf}(\frac{\log\tau - \mu}{\sigma\sqrt{2}} - \frac{\sigma \mathrm{n}}{\sqrt{2}})).$$

The resulting $\langle t \rangle$ versus σ curve is shown in Fig. 2(a). As can be seen, the portfolio has a cusp point that represents the restart time τ that is preferable to all others. No strategy exists in this case with a lower expected waiting time (at possibly the cost of a higher risk) or with a lower risk (at possibly the cost of a higher expected waiting time). The location of the cusp can be translated into the optimum value of the restart time to be used to reload the page.

There are many variations to the restart strategy described above. In particular, in Fig. 2(b), we show the family of curves obtained from the same distribution used in (a), but with a restriction on the maximum number of restarts allowed in each transaction. Even a few restarts yield an improvement.

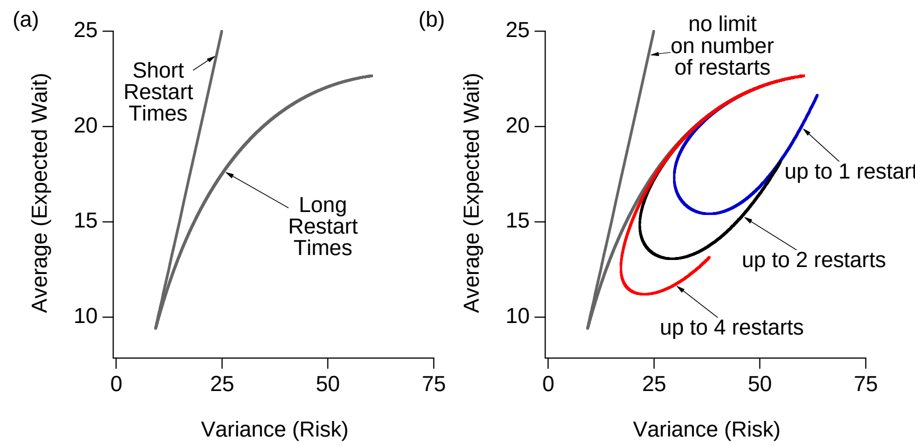

Figure 2: (a) Expected average latency versus risk (variance) calculated for a log-normal distribution with $\mu = 2$ and $\sigma = 1.5$. The curve is parametrized over a range of restart times. (b) Family of curves obtained when we limit the maximum number of allowed restarts.

Clearly, in a network without any kind of usage-based pricing, sending many messages to begin with would be the best strategy as long as we do not overwhelm the target computer. On the other hand, everyone can reason in exactly the same way, resulting in congestion levels that would render the network useless. This paradoxical situation, sometimes called a social dilemma, arises often in the consideration of "public goods" such as natural resources and the provision of services which require voluntary cooperation [6]. This explains much of the current interest in determining the details of an appropriate pricing scheme for the Internet, since users do consume Internet bandwidth greedily when downloading large multimedia files for example, without consideration of the congestion caused by such activity.

Note that the histogram in Figure 1 represents the variance in the download time between different sites, whereas a successful restart strategy depends on a variance in the download times for the same document on the same site. For this reason, we can not use the histogram in Figure 1 to predict the effectiveness of the restart strategy. While a spread in the download times of pages from different sites reduces the gains that can be made using a common restart strategy, it is possible to take advantage of geography and the time of day to fine tune and improve the strategy's performance. As a last resort, it is possible to fine tune the restart strategy on a site per site basis.

As a final caution, we point out that with current client-server implementations, multiple restarts will be detrimental and very inefficient since every duplicated request will enter the server's queue and will be processed separately until the server realizes that the client is not listening to the reply. This is

an important issue for a practical implementation, and we neglect it here: our main assumption will be that the restart strategy only affects the congestion by modifying the perceived latencies. This will only be true if the restart strategy is implemented in an efficient and coordinated way on both the client and server side.

3 Restart Strategies for Multiple Users

While restart strategies based on a portfolio approach may improve returns for a single user, it is important to consider whether the use of such strategies leads to a different dilemma. What happens when every user makes use of the restart strategy? This question is analogous to the problem of adjustments to equilibrium encountered in finance [7].

In order to investigate the effects on congestion of many agents using a restart strategy, we performed a series of computer simulations of a group of agents deciding asynchronously whether to use the Internet or not. The agents base their decision on knowledge of the congestion statistics over a past window of time. As shown by Huberman and Glance [9], such a collective action dilemma leads to an optimal strategy which is basically determined by a threshold function: cooperate if parameters of the problem are such that a critical function exceeds a certain value and defect otherwise. In terms of the dilemma posed by using the Internet [1] this translates into downloading pages if latencies are below a certain value and not doing so if they exceed a particular value. Thus, each agent is restricted to a simple binary decision, and the dynamics are those of a simple threshold model with uncertainties built in.

With this in mind, we model each agent as follows: an agent measures the current congestion, expressed in arbitrary "latency time" units. Since the latency is a function of the number of users, and their number fluctuates in time, it is reasonable to make the decision to use or not to use the restart strategy a function of the histogram of the load over a past window of time. This histogram is used to calculate the perceived latency time using different strategies, as described in the previous section. The agent compares the perceived latency to a threshold: if the former is larger, he decides to "cooperate" and refrains from using the Internet. If the latency is short enough, he decides to "defect". Agents make these decisions in an asynchronous fashion, with exponentially distributed waiting times [10].

We assume that the load created by an agent who decides to make use of the network's resources does not depend on whether or not he uses the restart strategy. This is only true if the server can efficiently detect multiple requests and cancel the superfluous ones, in order to avoid sending the same data to the client multiple times. Current implementations do not offer this feature. As a result, while a restart strategy may be beneficial to a single user, the net effect will be to cause more congestion.

In order to calculate the latency λ as a function of the number of users N_D, we use the average waiting time for a M/M/1 queue [11], with a capacity one

larger than the total number of agents N:

$$\lambda = 1/(1 + N - N_D).$$

Note that this simple M/M/1 queue model is not meant to provide anything more than an intuitive justification for the value of the latency and the qualitative behavior of its fluctuations (especially their correlations). In particular, the notion of a single M/M/1 queue is inconsistent with the idea of a restart strategy.

As it stands, this model would simply relax to an equilibrium in which the number of users is such that the latency is the threshold latency. To remedy this, we add fluctuations in the latency times using multiplicative noise (taken from a gaussian distribution with unit mean). This multiplicative noise will also be correlated in time (we model it as an Ornstein-Uhlenbeck process). This correlation is a crucial aspect of the model: agents who arrive at the same time should experience a similar congestion. If the noise were completely uncorrelated, agents might as well be on different networks. (We also performed simulations using additive noise. This produced no qualitative changes in the results).

A summary of the model is given in the appendix. It includes a list of all the parameters and the pseudocode for the simulation.

Since the restart strategy is designed to reduce the effect of congestion, we expect that as more users employ it the congestion will increase. However, this will be acceptable as long as the perceived latency *with* restarts does not become worse than the latency originally was without restarts. This should be the case, as the following mean field model indicates.

In a mean field model, f_d, the average fraction of agents who defect, is determined by the differential equation

$$\frac{df_d}{dt} = -\alpha(f_d - \rho(f_d)),$$

where in the context of this paper $\rho(f_d)$ is the average probability that the perceived latency is below threshold (i.e. the probability that a cooperating agent will decide to defect [8]), and α is the frequency with which agents evaluate their decisions to cooperate or not. The inverse of this frequency sets the time scale for all processes in the simulations. In the presence of imperfect knowledge modeled by a gaussian distribution (with width σ) of perceived utilities,

$$\rho(f_d) = \frac{1}{2}(1 + \mathrm{erf}(\frac{\mathrm{U(f_d) - U_c}}{\sigma\sqrt{2}}))$$

where $U(f_d)$ is the utility of defecting given that a fraction f_d of agents is defecting, and U_c is the threshold utility below while users will cooperate. Expanding

around values of f_d such that $U(f_d) = U_c$, and setting the right hand side of the differential equation equal to 0 in order to find the equilibrium point, we obtain

$$U(f_{equ}) = U_{equ} = U_c + \sqrt{2}\sigma(2f_{equ} - 1).$$

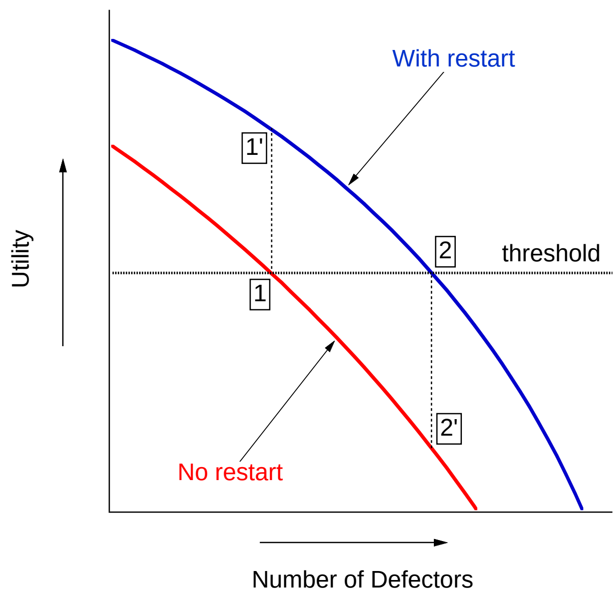

Figure 3: Qualitative expectations for the model. See text for description.

Thus, whatever the details of the threshold based multi-agent model, an average equilibrium number of defectors can be mapped onto an expected utility (where the utility may be a combination of both average latency and the variance in the latency). Clearly, the restart strategy will always provide a higher utility than no restart strategy, i.e. $U_{restart}(f) \geq U_{norestart}(f)$. However, the threshold utility remains the same. Thus, as Figure 3 illustrates for the case in which $\sigma = 0$, the equilibrium point is located at the intersection marked 1 when no agent is using the restart strategy, and by point 2 when all agents use the restart strategy. In the first case, a single agent who is using the restart strategy will benefit from a much larger utility (point 1'). However, when most agents do so, this advantage is lost, and the converse is true: if a few agents are opting to not use the restart strategy, they will experience a utility below threshold (point 2') and will cooperate (by not using bandwidth greedily). There are two other interesting conclusions to the analysis above if $\sigma > 0$. First, if $f_{equ} > 0.5$ the perceived equilibrium utility will be above threshold. Second, the average perceived utility will *increase* when all agents use the restart strategy. However, this latter effect will be small if the change in f_{equ} is small. Both these results are confirmed by the simulations.

To summarize, the utility perceived by the agents using the dominant strategy will not decrease as the strategy switches from no restart to restart. However, if a small number of agents decide not to switch to the restart strategy, they will obtain a lower utility than before. Thus, every agent is always better off using the restart strategy, even if everyone does so. There is no dilemma. However, such an argument does not model the effect of dynamics and fluctuations in a large agent population, which we now study.

4 Results

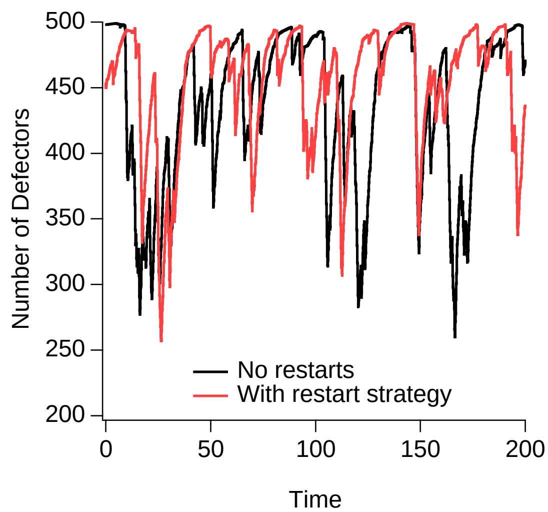

Figure 4: Time trace of the number of defectors, both with and without use of the restart strategy.

A typical trace of the number of defectors (network users) as a function of time is shown in Figure 4, with and without use of the restart strategy. The simulations were performed with 500 agents, a threshold latency λ_c of 0.05 and a variance in the noise of 0.01 with a correlation time of 1. The histogram was collected with a relaxation time of 10000 (in units of α^{-1}). While the differences between the two traces in Fig. 4 is difficult to see, the average number of defectors and the amplitude of the fluctuations were both larger when agents made use of the restart strategy, as expected.

The two portfolio curves that result from the simulation in Figure 4 are shown in Figure 5. The dotted line indicates the threshold latency: when agents do not use the restart strategy, the end point of the curve (corresponding to an infinitely long restart time) is expected to fall on the dotted line. In (a), when agents do use the restart strategy, the waiting time at the cusp equals

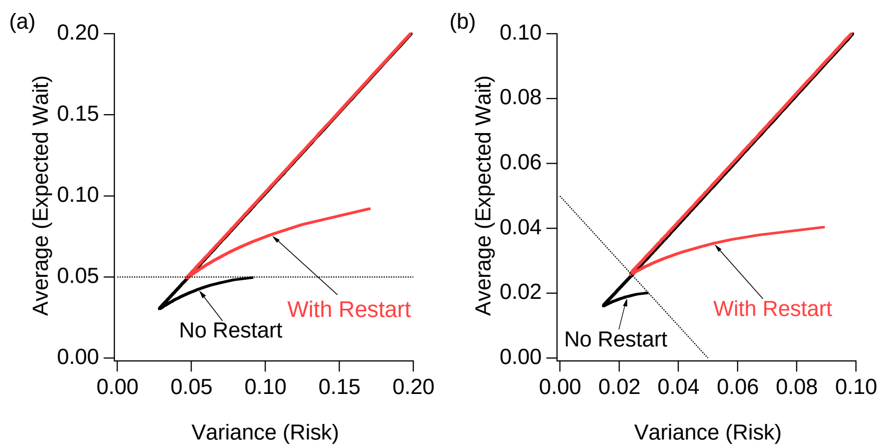

Figure 5: Average wait vs variance (risk) as a function of the optimum restart time when all agents do and do not make use the optimum restart strategy. The dotted line indicates the threshold indifference curve. (a) Agents are indifferent to risk. (b) Expected return and risk contribute equally to the utility function.

the threshold latency. As expected, the optimum point (cusp) shifts to higher average and variance as more agents make use of the restart strategy. Similarly, a single agent who does not make use of the restart strategy while every body else does will experience larger waiting times and larger risk, on average, than he would have experienced with nobody using the restart strategy. Note that the section of the portfolio curves corresponding to very short restart times falls on the $y = x$ line – this can be verified by expanding the expressions for $\langle t \rangle$, $\langle t^2 \rangle$ and $p(t)$ for small restart times τ.

Figure 6 shows the behavior of the expected waiting time as a function of the restart time. As more agents make use of the restart strategy, the optimum restart time (corresponding to the minimum expected waiting time) shifts to larger values.

We performed an extensive set of simulations to check these results as the parameters of the model were varied. Very short correlation times washed out the interactions between different agents, effectively placing them on different networks – the restart strategy had no effect. As the correlation time was made larger, so that a large fraction of the agents effectively updated their decisions simultaneously, the restart strategy became more effective. In fact, other than causing a shift in the equilibrium latencies, noise amplitude played a relatively minor role compared to the fluctuations due to the interaction of agents (modelled by the correlations in the noise).

To first order, the amplitude of the noise fluctuations had a relatively minor effect. However, Figure 7 illustrates one of the predictions made by the mean field theory illustrated in Figure 3: a large variance will lead to an increased

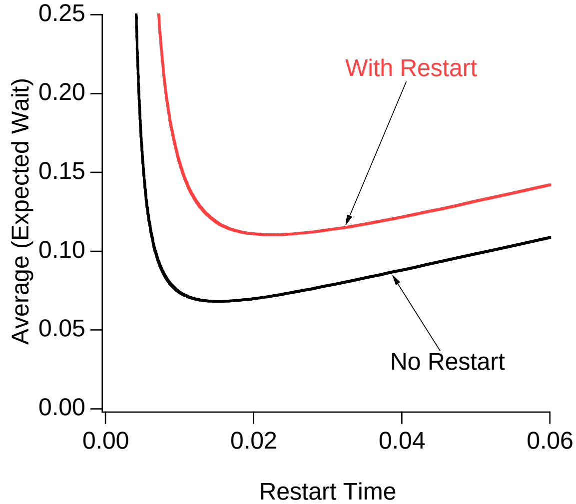

Figure 6: Average waiting time (latency) as a function of the restart time, with and without use of the restart strategy.

utility (lower latency) if $f_{equ} > 0.5$ but to a decreased utility (higher latency) if $f_{equ} < 0.5$.

Figure 8 illustrates the portfolios that result from a mix of agents using and not using the restart strategy. As the number of agents aware of the restart strategy increases, the optimum point shifts to lower variance but higher mean latency, until the mean latency at optimum restart equals the threshold. Until that point, the variance for agents not using the restart strategy also decreases. Once the number of restart agents becomes too large, the network is too congested and the remaining agents defect.

5 Conclusion

In this paper we have shown that when every agent uses a portfolio strategy in order to deal with Internet congestion, there is a range of parameters such that a) a portfolio exists and b) all agents are better off using it than not. Even when all agents use the optimum restart strategy, the situation is no worse than the situation in which no one uses the restart strategy. This solution was obtained both by using mean field arguments and computer simulations that took into account the dynamics of agent decisions and discounted past information on network conditions. These solutions, which show the existence of a possibly noisy fixed point, illustrate the power of simulations in understanding multiagent dynamics under varying dynamical constraints.

In economics, the existence of a unique and stable equilibrium is usually considered without taking dynamics into account. Using a physics metaphor,

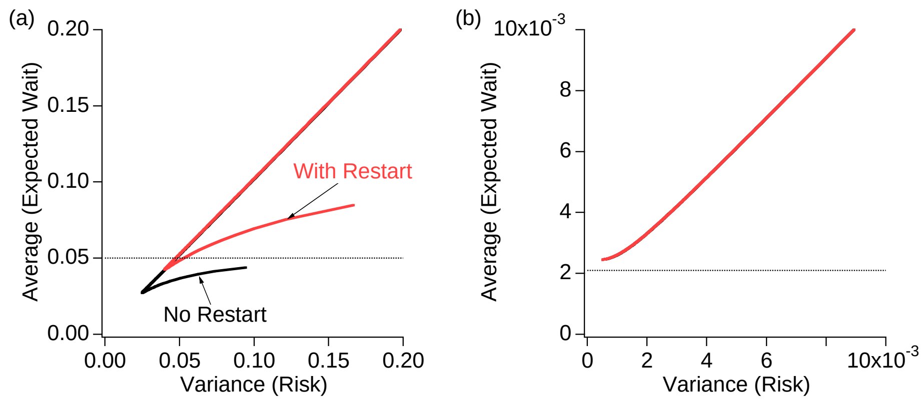

Figure 7: Portfolio curves for the same parameters as in Figure 5, except that $\sigma = 0.2$. (a) The threshold latency was $\lambda_c = 0.05$. This was high enough that more than half the agents defected, on average. Thus, the equilibrium latencies were lower than the threshold latency, both with a without use of the restart strategy, as predicted by the mean field theory. (b) The threshold latency was very low, $\lambda_c = 0.0021$, so that a very small number of agents defected. Note that the equilibrium point occured at average latencies higher than the threshold. Also note that for there parameters, use of the restart strategy or not does not affect the perceived latencies – both portfolio curves overlap.

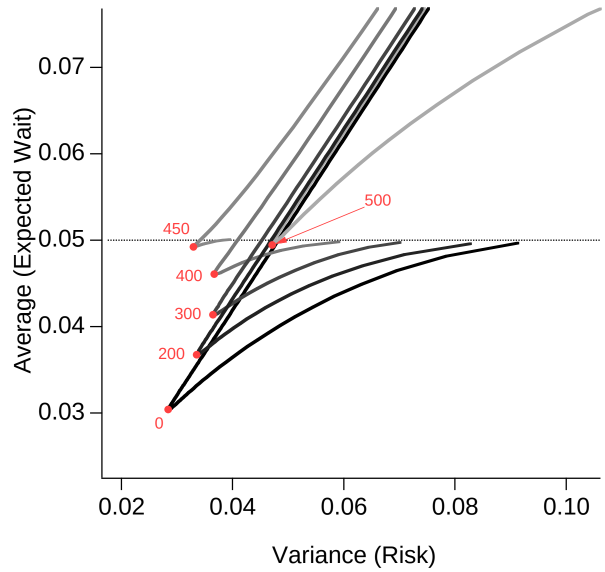

Figure 8: Portfolio curves as the number of agents using the restart strategy changes from 0 (no agent) to 500 (all agents).

this is equivalent to overdamped or viscous dynamics in which velocity (rate of change in time) does not matter. And yet, we know of a number of economic systems which are continuously changing and sometimes are unable to reach an equilibrium. Agent based simulations [12][13], combined with simple analytic models, are powerful tools to study dynamic effects, since new assumptions can be implemented and tested rapidly, and be compared to mean field theories in order to verify their applicability.

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A Model Parameters and Pseudocode

A.1 Parameters

- Number of agents N
- Number of agents using restart strategy N_R
- Histogram relaxation rate τ_H
- Noise correlation time τ
- Threshold latency λ_c
- Noise variance σ (noise mean is 1.0)

The reevaluation rate α for a single agent sets the time scale for the model. We also need a function to map the number of agents using the network into an average expected latency. We use the functional dependence expected for a M/M/1 queue with a capacity larger than the number of users.

A.2 Pseudocode

REPEAT
    Pick a time step Δt
        exponential random deviate with mean $\frac{1}{N\alpha}$

    Update running user histogram
        Discount histogram using τ_H
        Add Δt to appropriate bin

    Pick an agent randomly

    Compute the perceived average latency λ
        based on the running histogram and the
        chosen agent's strategy

    Multiply λ by $1 + N(0, \sigma^2)$
        $N(m, \sigma^2)$ is a normal distribution with mean μ and variance σ^2

    IF $(\lambda < \lambda_c)$
        Agent does use the network (defect)
    ELSE
        Agent does not use the network (cooperate)

END REPEAT